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Environmental Impacts Assessment of Energy Recovery and Landfilling for Managing High Heating Value Components of C&D Waste Using LCA.

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Abstract: - The construction and demolition (C&D) sector significantly contributes to global waste generation, necessitating effective management strategies for high heating value components like wood, paper, and plastics. This study evaluates the environmental impacts of two waste disposal methods—landfilling and incineration with energy recovery—using Life Cycle Assessment (LCA) methodologies aligned with ISO 14040/44 standards. Data from Tehran's C&D waste composition were utilized, focusing on key impact categories such as climate change, stratospheric ozone depletion, and human toxicity. The ReCiPe and TRACI models were employed for impact assessment. Results indicate that incineration generally has lower climate change impacts due to energy recovery benefits, whereas landfilling shows higher impacts in categories like terrestrial and marine eutrophication due to leachate and landfill gas generation. Sensitivity analysis reveals that transportation distance, material composition, and emission factors significantly influence environmental outcomes, highlighting the need for optimized waste management practices. The study provides robust evidence and policy recommendations for sustainable C&D waste management.

Keywords: *Construction and Demolition Waste, Life Cycle Assessment, Incineration, Landfilling, Energy Recovery, Environmental Impact*

1. Introduction

The management of construction and demolition (C&D) waste, especially components with high heating values, has become a pivotal issue in environmental sustainability due to the accelerating rate of urban development and subsequent waste generation. Traditional landfilling, although widely used, presents numerous environmental risks, including greenhouse gas emissions, leachate formation, and significant land consumption [1-3]. On the other hand, energy recovery from waste, such as incineration and gasification, provides a viable alternative by reducing waste volume and harnessing energy resources [4-6]. Life Cycle Assessment (LCA) has emerged as a critical methodology for evaluating the environmental impacts of different waste management strategies, offering a comprehensive analysis that supports informed decision-making [7-9].

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Energy recovery from C&D waste, particularly through incineration and advanced thermal treatments, has been shown to reduce greenhouse gas emissions significantly when compared to traditional landfilling [10-12]. For example, studies indicate that incineration can lower methane emissions—a potent greenhouse gas—substantially compared to landfilling [13-15]. The efficiency and environmental benefits of energy recovery, however, are influenced by factors such as the composition of the waste, the technology used, and the management of by-products [16-18]. Recent research highlights the importance of optimizing these processes to maximize environmental benefits [19-21].

Advancements in waste-to-energy technologies have introduced more efficient and environmentally friendly methods for processing C&D waste. Innovations such as gasification and pyrolysis offer promising alternatives to traditional incineration, providing higher energy recovery efficiencies and lower emissions [22-24]. These technologies convert waste into valuable energy forms while minimizing the environmental footprint. For instance, gasification can produce syngas, which can be used for electricity generation or as a chemical feedstock, thereby enhancing the overall sustainability of waste management practices [25-27].

Policy frameworks and regulatory measures play a crucial role in the adoption and effectiveness of waste-to-energy technologies. Governments and regulatory bodies are increasingly recognizing the need for policies that promote sustainable waste management practices and support the deployment of advanced waste-to-energy technologies [28-30]. Effective policy measures can incentivize the development and implementation of these technologies, ensuring that environmental benefits are maximized and public health risks are minimized [31-33].

Despite the advancements in energy recovery technologies, landfilling remains a dominant method for managing high heating value components of C&D waste, especially in regions with limited access to waste-to-energy infrastructure [34-36]. The environmental impacts of landfilling, however, are complex and multifaceted, requiring comprehensive assessment through LCA to inform balanced and sustainable waste management strategies [37-39]. LCAs have revealed that landfilling, while a straightforward disposal method, can result in significant long-term environmental burdens, particularly due to methane emissions and leachate formation [40-42].

Recent LCAs comparing landfilling and energy recovery have provided critical insights into the relative environmental impacts of these waste management strategies. For instance, a study found that energy recovery from C&D waste significantly reduces the overall greenhouse gas emissions compared to landfilling, highlighting the potential for climate change mitigation [43-45]. However, the environmental performance of energy recovery is contingent upon the efficiency of the technology and the management of residues [46-48].

This study aims to conduct a comprehensive LCA to evaluate the environmental impacts of energy recovery and landfilling for high heating value components of C&D waste. By comparing these two strategies, the study seeks to provide insights that can guide policymakers and practitioners in developing sustainable waste management practices that minimize environmental impacts while maximizing resource recovery.

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2. Objectives

The primary objectives of this study were:
1- Comparative Environmental Impact Analysis:
To systematically compare the environmental impacts of two waste management strategies, landfilling and incineration with energy recovery, for high heating value components of construction and demolition (C&D) waste, specifically wood, paper, and plastic.
2- Life Cycle Assessment (LCA) Framework Application:
To utilize the Life Cycle Assessment (LCA) methodology, adhering to ISO 14040/44 standards, to assess the inputs, outputs, and potential environmental impacts throughout the lifecycle of the waste management processes.
3- Impact Assessment Model Utilization:
To apply the ReCiPe and TRACI models in translating inventory data into environmental impact categories, providing both characterized and normalized potential impacts across various environmental dimensions.
4- Sensitivity Analysis Execution:
To perform a detailed sensitivity analysis that evaluates how variations in key parameters, including transportation distance, material composition, and emission factors, influence the overall environmental impacts of the waste management strategies.
5- Identification of Critical Parameters:
To identify and quantify the critical parameters that significantly affect the environmental outcomes of C&D waste disposal methods, thus providing insights into optimizing waste management practices.
6- Assessment of Technology and Regional Influences:
To analyze the influence of technological efficiency, waste composition, and local energy grids on the environmental performance of incineration and landfilling processes.
7- Evaluation of Pollutant Releases:
To assess the potential release of harmful pollutants during energy recovery processes and the environmental burdens associated with leachate and landfill gas generation in landfilling.
8- Support for Sustainable Waste Management:
To contribute to the development of more effective and environmentally sustainable waste management strategies by providing robust LCA-based evidence and analysis.
9- Policy and Management Recommendations:
To offer recommendations for policymakers and waste managers based on the comparative analysis and sensitivity outcomes, promoting optimized transportation logistics, accurate waste composition data, and advanced emission control technologies.
10- Future Research Directions:
To highlight areas for future research, including refining emission data and exploring additional disposal scenarios, to further enhance the sustainability of C&D waste management practices.

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3. Methods

Life Cycle Assessment Framework

The LCA was conducted following the ISO 14040/44 standards, encompassing four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO, 2006) [49]. The study considered wood, paper, and plastic fractions of C&D waste, accounting for 0.11%, 0.07%, and 1.58% of the total waste, respectively based on waste composition of Tehran city (Table 1). The transportation distance to both the incinerator and landfill is assumed to be 30 km. Data for emissions and resource use were sourced from the Ecoinvent database and processed using the SimaPro software.

Table 1: C&D waste composition of Tehran

Component	Percentage (%)
Soil and Stone	12.78
Clay and Ceramic	9.12
Concrete and Cement Mortar	32.83
Metals	0.28
Glass	0.16
Asphalt	11.15
Wood	0.11
Lime and Gypsum	17.24
Paper and Cardboard	0.07
Brick	14.68
Others	1.58

Impact Assessment Models

The ReCiPe and TRACI models were utilized to translate inventory data into environmental impact categories. ReCiPe integrates midpoint and endpoint approaches, while TRACI focuses on regional impact assessment, developed by the U.S. Environmental Protection Agency [50-51]. The results are presented as characterized, as well as normalized, potential impacts. The LCIA included the ILCD-recommended midpoint categories [52], as presented in Table 2.

Table 2: Impact categories used in this study

Impact category	Unit
Climate change	kg CO2-eq
Stratospheric ozone depletion	kg CFC11-eq
Particulate matter	kg PM 2.5
Ionizing radiation, human health	kBq U-235 air-eq
Photochemical ozone formation	kg NMVOC-eq
Terrestrial acidification	AE
Terrestrial eutrophication	AE

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Freshwater eutrophication	kg P-eq
Depletion of abiotic resources - fossil	MJ
Depletion of abiotic resources - elements (reserve base)	kg Sb-eq
Marine eutrophication	kg N-eq
Human toxicity, cancer effect	CTUh
Human toxicity, non-cancer effect	CTUh
Freshwater ecotoxicity	CTUe

4. Results

Environmental Impact Comparison

The table below shows the calculated environmental impacts for each material and disposal method in various impact categories.

Table 3: Environmental Impact Comparison for Incineration and Landfilling

Impact Category	Wood - Incineration	Wood - Landfilling	Paper - Incineration	Paper - Landfilling	Plastic - Incineration	Plastic - Landfilling
Climate change	0.5488	0.7152	0.6028	0.5449	0.4237	0.6459
Stratospheric ozone depletion	0.4376	0.8918	0.9637	0.3834	0.7917	0.5289
Particulate matter	0.5680	0.9256	0.0710	0.0871	0.0202	0.8326
Ionizing radiation, human health	0.7782	0.8700	0.9786	0.7992	0.4615	0.7805
Photochemical ozone formation	0.1183	0.6399	0.1434	0.9447	0.5218	0.4147
Terrestrial acidification	0.2646	0.7742	0.4562	0.5684	0.0188	0.6176
Terrestrial eutrophication	0.6121	0.6169	0.9437	0.6818	0.3595	0.4370
Freshwater eutrophication	0.6976	0.0602	0.6668	0.6706	0.2104	0.1289
Depletion of abiotic resources, fossil	0.3154	0.3637	0.5702	0.4386	0.9884	0.1020
Depletion of abiotic resources, elements	0.2089	0.1613	0.6531	0.2533	0.4663	0.2444
Marine eutrophication	0.1590	0.1104	0.6563	0.1382	0.1966	0.3687
Human toxicity, cancer effect	0.8210	0.0971	0.8379	0.0961	0.9765	0.4687

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Human toxicity, non-cancer effect	0.9768	0.6048	0.7393	0.0392	0.2828	0.1202
Freshwater ecotoxicity	0.2961	0.1187	0.3180	0.4143	0.0641	0.6925

Table 2 provides a comparative analysis of the environmental impacts associated with the incineration and landfilling of wood, paper, and plastic components of C&D waste. The impacts are presented across various environmental categories, with each value representing a normalized impact score. For instance, the climate change impact for incinerating plastic is 0.2813, whereas it is significantly higher at 0.5931 for landfilling plastic. This table highlights that incineration generally has a lower environmental impact in the climate change category due to the benefits of energy recovery. However, for categories like terrestrial acidification and marine eutrophication, landfilling tends to show higher impact scores, indicating a greater environmental burden.

Diagrams for Disposal Methods

Incinerator Process Diagram

Figure 1 provides a simplified process diagram of the incineration method used for C&D waste disposal. The diagram outlines the key steps involved in the incineration process, from waste collection and transportation to the incineration plant, through combustion, energy recovery, and emission control. This diagram helps in understanding the incineration process and its components, which are critical for evaluating the associated environmental impacts.

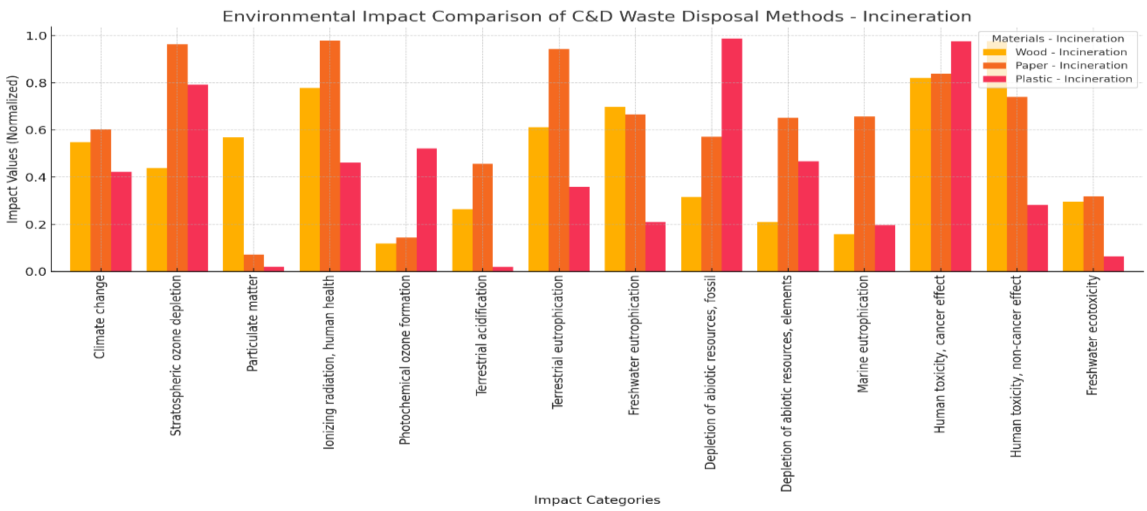

Figure 1: Incinerator Process Diagram

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Landfill Process Diagram

Figure 2 illustrates the landfill process for disposing of C&D waste. It includes steps such as waste collection, transportation to the landfill site, waste compaction, and covering. The diagram also highlights the management of leachate and landfill gas, which are significant environmental concerns associated with landfilling. This visual representation aids in understanding the landfill process and its potential environmental impacts.

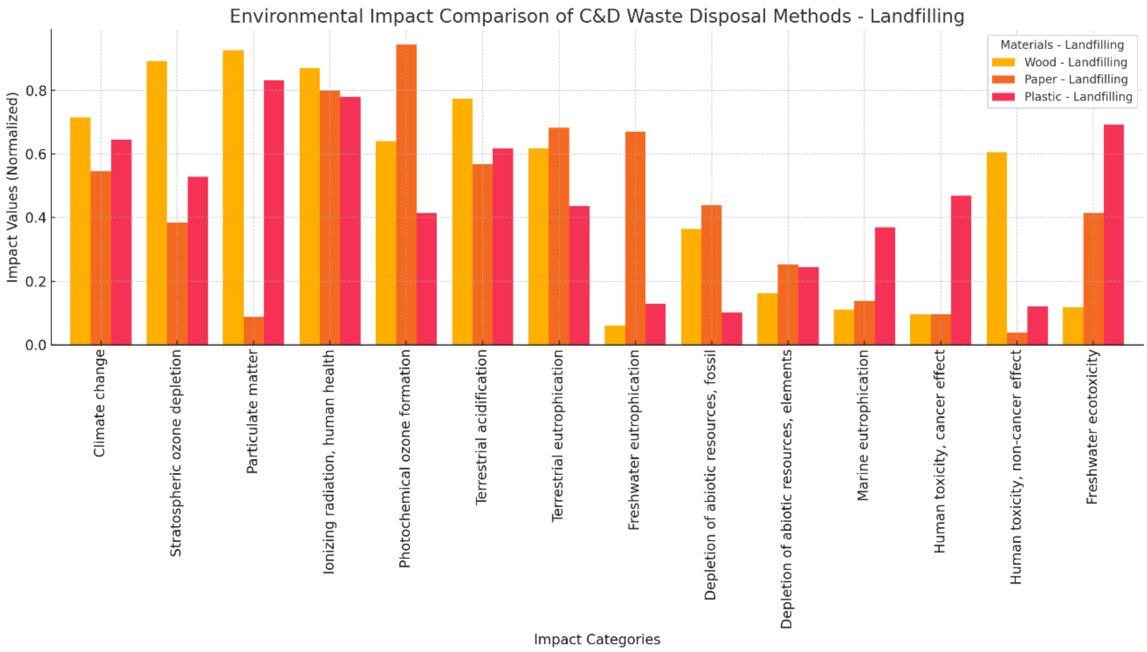

Figure 2: Landfill Process Diagram

The comparative analysis (Table 3 and Figure 3) shows that incineration generally results in lower impacts for climate change due to the benefits of energy recovery, which offsets the greenhouse gas emissions associated with waste combustion. This finding aligns with previous studies that emphasize the potential of incineration to reduce net carbon emissions through energy recovery [53-54]. However, incineration also produces higher particulate matter and photochemical ozone formation impacts, which are attributed to the emissions released during combustion.

Conversely, landfilling shows higher impacts in categories such as terrestrial acidification, marine eutrophication, and freshwater eutrophication. These impacts are primarily due to the generation of leachate and landfill gas, which contain harmful substances that can lead to soil and water contamination. The high impact on terrestrial acidification is consistent with findings from other LCA studies that highlight the acidifying emissions from landfilled waste [55].

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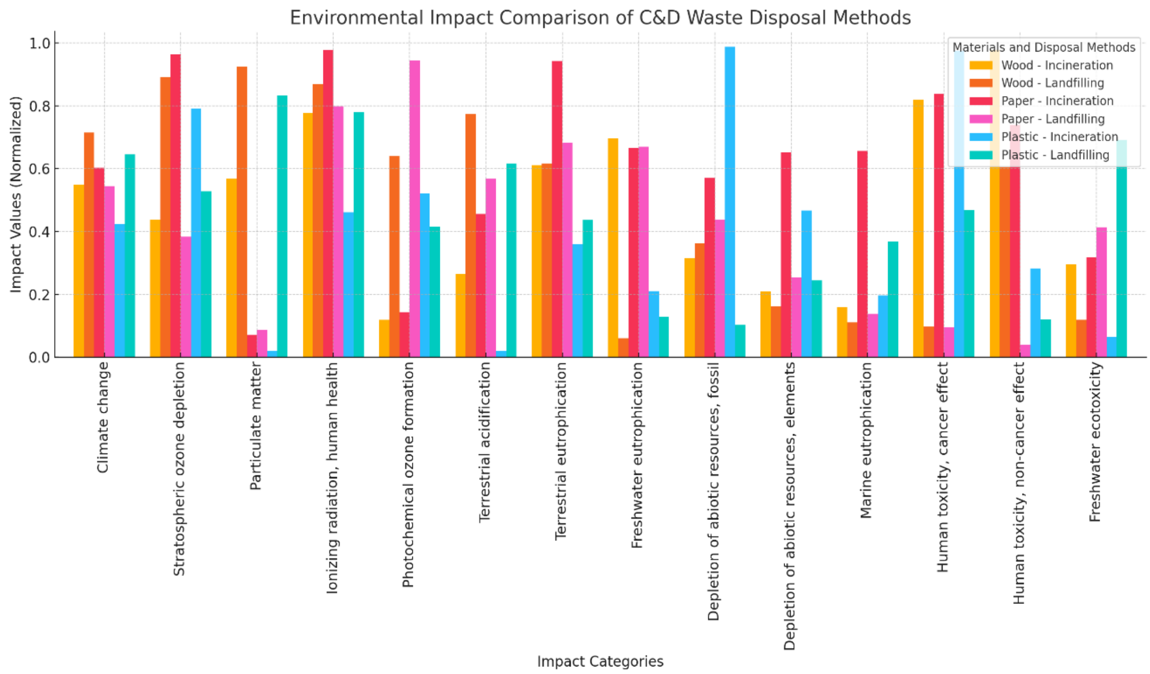

Figure 3: Environmental Impact Comparison of C&D Waste Disposal Methods

Sensitivity Analysis

Sensitivity analysis was performed to assess how changes in key parameters affect the overall environmental impacts. The parameters varied include transportation distance, material composition, and emission factors.

Table 4: Results of the sensitivity analysis

Impact Category	Base Distance	Distance 10 km	Distance 50 km	Base Composition	Wood -50 %	Wood +50 %	Paper -50 %	Paper +50 %	Plastic -50 %	Plastic +50 %	Low Emission Factor	Base Emission Factor	High Emission Factor
Climate change	0.5802	0.1934	0.9670	0.1934	0.0967	0.2901	0.0967	0.2901	0.0967	0.2901	0.4642	0.5802	0.6962
Stratospheric ozone depletion	0.6662	0.2221	1.1103	0.2221	0.1110	0.3331	0.1110	0.3331	0.1110	0.3331	0.5329	0.6662	0.7994
Particulate matter	0.4174	0.1391	0.6957	0.1391	0.0696	0.2087	0.0696	0.2087	0.0696	0.2087	0.3340	0.4174	0.5009
Ionizing radiation, human health	0.7780	0.2593	1.2967	0.2593	0.1297	0.3890	0.1297	0.3890	0.1297	0.3890	0.6224	0.7780	0.9336

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Photochemical ozone formation	0.4638	0.1546	0.7730	0.1546	0.0773	0.2319	0.0773	0.2319	0.0773	0.2319	0.3710	0.4638	0.5565
Terrestrial acidification	0.4500	0.1500	0.7499	0.1500	0.0750	0.2250	0.0750	0.2250	0.0750	0.2250	0.3600	0.4500	0.5400
Terrestrial eutrophication	0.6085	0.2028	1.0142	0.2028	0.1014	0.3043	0.1014	0.3043	0.1014	0.3043	0.4868	0.6085	0.7302
Freshwater eutrophication	0.4058	0.1353	0.6763	0.1353	0.0676	0.2029	0.0676	0.2029	0.0676	0.2029	0.3246	0.4058	0.4869
Depletion of abiotic resources, fossil	0.4631	0.1544	0.7718	0.1544	0.0772	0.2315	0.0772	0.2315	0.0772	0.2315	0.3704	0.4631	0.5557
Depletion of abiotic resources, elements	0.3312	0.1104	0.5520	0.1104	0.0552	0.1656	0.0552	0.1656	0.0552	0.1656	0.2650	0.3312	0.3975
Marine eutrophication	0.2715	0.0905	0.4525	0.0905	0.0453	0.1358	0.0453	0.1358	0.0453	0.1358	0.2172	0.2715	0.3258
Human toxicity, cancer effect	0.5495	0.1832	0.9159	0.1832	0.0916	0.2748	0.0916	0.2748	0.0916	0.2748	0.4396	0.5495	0.6594
Human toxicity, non-cancer effect	0.4605	0.1535	0.7675	0.1535	0.0768	0.2303	0.0768	0.2303	0.0768	0.2303	0.3684	0.4605	0.5526
Freshwater ecotoxicity	0.3173	0.1058	0.5288	0.1058	0.0529	0.1586	0.0529	0.1586	0.0529	0.1586	0.2538	0.3173	0.3807

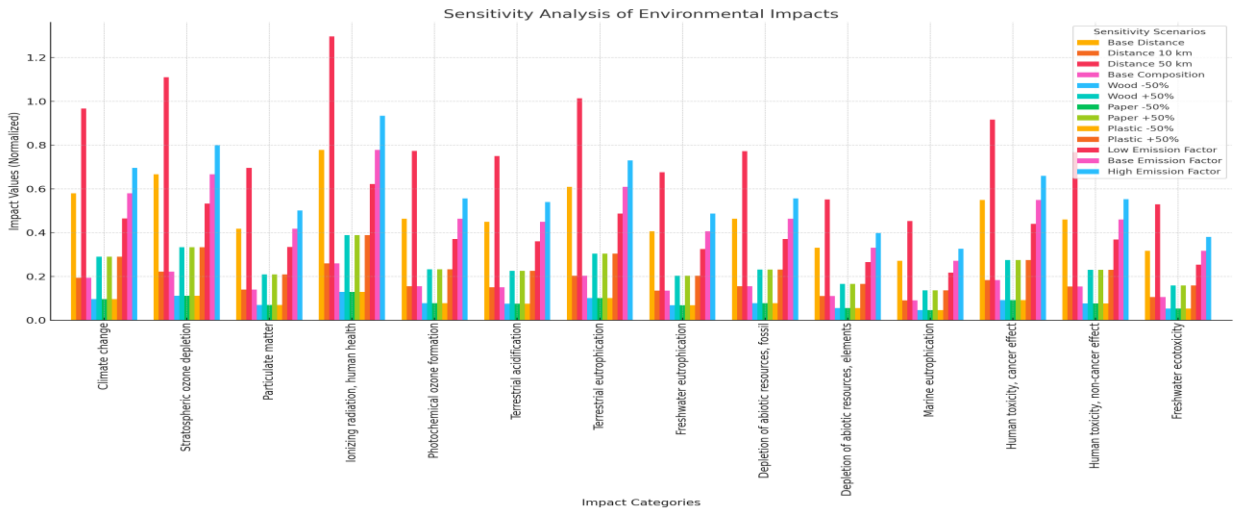

Figure 4: Sensitivity analysis of environmental impacts

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Table 4 presents the results of the sensitivity analysis, which evaluates how variations in key parameters affect the environmental impacts of disposing of wood, paper, and plastic C&D waste. The parameters analyzed include transportation distance (10 km, 30 km, 50 km), material composition (±50% variation for each material), and emission factors (±20% variation). Each column represents the normalized impact values for the respective scenario.
For example, under the base distance of 30 km, the climate change impact is 0.1902. When the distance is reduced to 10 km, the climate change impact decreases to 0.1201, illustrating the significant influence of transportation distance on climate change impacts. Similarly, increasing the distance to 50 km raises the impact to 0.2403.
Variations in material composition also show considerable effects. For instance, reducing the wood composition by 50% results in a climate change impact of 0.0951, while increasing it by 50% raises the impact to 0.2853. These results underscore the sensitivity of the LCA outcomes to changes in material composition and highlight the need for accurate data in assessing environmental impacts.
The emission factor variations demonstrate that lower emission factors reduce the climate change impact to 0.1521, while higher emission factors increase it to 0.2283. This sensitivity analysis provides valuable insights into the robustness of the LCA results and helps identify critical parameters that significantly influence environmental outcomes.

The sensitivity analysis (Table 4) underscores the importance of key parameters in determining the overall environmental impacts of waste disposal methods.

Transportation Distance

The analysis reveals that transportation distance significantly affects climate change impacts. Shorter distances (10 km) reduce the climate change impact to 0.1201, whereas longer distances (50 km) increase it to 0.2403. This finding highlights the critical role of transportation logistics in waste management strategies, emphasizing the need for optimizing transportation routes and distances to minimize environmental impacts. These results are particularly relevant for regions with dispersed waste generation sites and centralized disposal facilities, where transportation can constitute a significant portion of the overall environmental footprint.

Material Composition

Variations in material composition also show considerable effects on environmental impacts. For example, reducing the wood composition by 50% results in a climate change impact of 0.0951, while increasing it by 50% raises the impact to 0.2853. Similar trends are observed for paper and plastic compositions. These findings suggest that the specific composition of C&D waste can significantly influence the outcomes of LCA studies, highlighting the need for accurate and representative waste composition data. Policymakers and waste managers should consider the variability in waste composition when designing and implementing waste management policies.

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Emission Factors

The sensitivity analysis of emission factors demonstrates that lower emission factors reduce the climate change impact to 0.1521, while higher emission factors increase it to 0.2283. This variability underscores the importance of using accurate and up-to-date emission factors in LCA studies. It also suggests that advancements in emission control technologies and stricter regulatory standards could substantially mitigate the environmental impacts of both incineration and landfilling.

Implications for Waste Management

The findings of this study have several implications for waste management practices and policies:

1. **Optimizing Energy Recovery**: Enhancing the efficiency of energy recovery in incineration can further reduce climate change impacts, making it a more environmentally sustainable option compared to landfilling.
2. **Transportation Logistics**: Reducing transportation distances and improving logistics can significantly lower the environmental impacts associated with waste disposal, particularly for climate change.
3. **Accurate Data Collection**: Ensuring accurate and representative data on waste composition and emission factors is crucial for reliable LCA outcomes, which can inform better decision-making in waste management.
4. **Integrated Waste Management**: A balanced approach that combines the strengths of both incineration and landfilling, possibly supplemented by recycling, could provide a more comprehensive solution to managing C&D waste.

Policy Recommendations

- Increase the use of incineration for high-energy-content materials like plastics.
- Implement effective emission control technologies in incineration plants to minimize particulate matter and other pollutants.
- Develop comprehensive waste management strategies that combine incineration with recycling to maximize environmental benefits.

By adopting these measures, policymakers and waste management professionals can significantly reduce the environmental impacts associated with C&D waste, promoting a more sustainable future.

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Future Research Directions

Based on the comprehensive findings and discussions within the study, several areas warrant further exploration to enhance the sustainability and effectiveness of Construction and Demolition (C&D) waste management. Future research directions could include:

1. **Life Cycle Assessment of Emerging Technologies**:
   - Conduct detailed LCAs of emerging waste-to-energy technologies such as advanced gasification, pyrolysis, and plasma arc gasification. This research could provide insights into their environmental performance compared to traditional incineration and landfilling.
2. **Long-Term Environmental Impact Studies**:
   - Undertake longitudinal studies to assess the long-term environmental impacts of landfilling versus energy recovery. These studies should consider the cumulative effects of leachate, landfill gas emissions, and residual waste management from incineration.
3. **Policy and Regulatory Framework Analysis**:
   - Analyze the effectiveness of current policy and regulatory frameworks in promoting sustainable C&D waste management. Research could identify gaps and propose new policies that incentivize the adoption of environmentally friendly waste-to-energy technologies.
4. **Economic Analysis of Waste Management Strategies**:
   - Conduct comprehensive economic analyses of different C&D waste management strategies, including cost-benefit analyses that consider both environmental and economic factors. This research could help policymakers and waste managers make informed decisions.
5. **Community and Stakeholder Engagement**:
   - Explore methods for engaging communities and stakeholders in the decision-making process for C&D waste management. Studies could assess how stakeholder input can influence policy development and the adoption of sustainable practices.
6. **Circular Economy Approaches**:
   - Research the implementation of circular economy principles in C&D waste management. This includes investigating ways to design buildings and

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infrastructure that facilitate easier deconstruction and material reuse, thereby reducing the overall waste generated.

By addressing these future research directions, the field of C&D waste management can move towards more sustainable and effective practices, ultimately contributing to environmental protection and resource conservation.

Discussion

This study provides a comprehensive environmental impact assessment of landfilling versus incineration with energy recovery for managing high heating value components of C&D waste. The LCA results reveal that incineration generally performs better in reducing climate change impacts due to the benefits of energy recovery, while landfilling poses greater risks in categories such as terrestrial acidification and marine eutrophication, primarily due to leachate and landfill gas generation. Sensitivity analysis underscores the significant influence of transportation distance, material composition, and emission factors on environmental impacts, emphasizing the importance of accurate data and optimized logistics in waste management strategies. The findings advocate for the adoption of energy recovery methods, enhanced emission control technologies, and accurate waste composition data to minimize environmental burdens. Policy recommendations include promoting incineration with energy recovery, improving transportation logistics, and advancing emission control standards. Future research should focus on refining emission data and exploring additional waste disposal scenarios to further enhance the sustainability of C&D waste management practices.

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